ULTRALUMINOUS INFRARED GALAXIES

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Picture

ABSTRACT One of thc most important results of the IRAS mission was the establishment that there exists a class of galaxies which emit over 90% of their energy in the far infrared. Some of these galaxies are extremely luminous, emitting more than $10^{12} L_\odot$ at $\lambda > 10\mu m$. The source of the energy for the quasar-like luminosities of these "ultraluminous infrared galaxies" is thought to bc either dust-obscured AGN and/or energetic starbursts. ‘l’he evidence in support of these two pictures is reviewed. A VLBI search for obscured AGN in the cores of some of the most luminous galaxies is then described.

1 INTRODUCTION

It has been known since the early seventies that some galaxies emit a large fraction of their total energy in the infrared (Rieke and Low 1972), but it took the IRAS mission to establish how important these objects are as a class. This is illustrated most simply in Figure 1, in which a luminosity function derived from IRAS data for field galaxies at $60\mu m$ is compared to an optical luminosity function: in the far-infrared there is an excess tail to high luminosities, extending to $10^{12} L_\odot$ (H = 75 km/s/Mpc) and beyond, that is not seen in optical field galaxy luminosity functions (Soifer *et al.* 1987; Rieke and Lebofsky 1986; Saunders *et al.* 1990; Sanders, Scoville and Soifer 1991).

Fig. 1. ***Comparison of a $60\mu m$ luminosity junction (Soifer et al. 1987; filled squares) to a blue luminosity junction for field galaxies (Efstathiou et al. 1988; solid line). There is an excess of luminous far-infrared bright galaxies above ~ 10111.0.***

It follows that there is a large range in the ratio of energy emitted in the far-infrared to that in the optical region of the spectrum among field galaxies, and it has been generally found that the infrared luminosity L_{IR} is correlated with increasing L_{IR}/L_B (Soifer *et al* 1987). The most luminous infrared galaxies can emit 99% of their energy beyond a few microns. The so-called ***ultraluminous infrared galaxies*** (hereafter UL galaxies) arc usually defined as having $L_{IR} \geq 10^{12} L_0$, though the usage of the term is somewhat imprecise. Soifer *et al.* showed that infrared-bright galaxies arc the dominant galaxy population at $L_{IR} > 3 \times 10^{11} L_\odot$, and above $10^{12} L_\odot$ the UL galaxies outnumber classical QSOS by a factor of 2.

'l'he fact that for far-infrared-bright galaxies in general L_{IR} correlates with L_{IR}/L_B but L_B dots not correlate with this ratio implies that we arc witnessing an additional IR energy source in these highly far-infrared-dominated galaxies, rather than an unusually strong extinction of the blue light. The very high luminosities of the UL galaxies also argue directly for an additional energy source. It has been found that the 60- $100\mu m$ color temperature increases with L_{IR}/L_B (Soifer *et al.;* Bothun, Lonsdale and Rice 1989; Saunders *et al.* 1990), implying that the additional energy source is dominated by warmer dust than the general far-infrared emission of galaxy disks, which arises both in star forming complexes and the diffuse ISM.

There is convincing evidence that far-infrared activity in galaxies is related to galaxy interactions and mergers. For far-infrared-selected samples, the fraction of galaxies that arc interacting increases with L_{IR} (see the recent reviews by Heckman 1991 b, Kennicutt 1991, and Sanders 1992, and references therein), Also, the stronger the interaction, the higher the infrared luminosity (Sanders *et al.* 1988a; Leech *et al.* 1989; Rowan-Robinson 1991).

Sanders *et al.* (1988a) have concluded that 100% of the ultraluminous galaxies that they studied are pairs in the process of merging. Further evidence for advanced mergers comes from the discovery that many ultraluminous galaxies have double nuclei, most of which are only observable at near-infrared or radio wavelengths due to heavy dust obscuration (Carico *et al.* 1990; Graham *et al.* 1990; Mozzarella *et al.* 1991; Majewski *et al.* 1993). It seems that there is a good correlation between the advanced merger morphology and ultraluminous infrared emission, implying that the timescales for these two phenomena must be quite similar: on the order of a few 10^7 years. The correlation between interaction morphology and enhanced infrared emission is not well established for lower luminosity systems.

The energy sources in UL galaxies appear to be strongly centrally concentrated. Radio continuum (Condon *et al.* 1990) and molecular line observations (Scoville *et al.* 1991) imply source radii no more than a few hundred parsecs in most cases, and as small as about 100 pc for some of the most luminous objects (Condon *et al.* 1991).

2 ENERGY SOURCES

The paramount question concerning the UL galaxies is of course the nature of the energy source(s) for the infrared luminosity. 'J'he most obvious contenders arc a burst of massive star formation or a heavil y obscured A GN. The first is an attractive and natural explanation because star-forming regions in our own and other galaxies have long been known to be strong sources of far-infrared emission (Thronson and Harper 1979; Telesco and Harper 1980; Telesco 1988), and because some starbursts arc thought to be triggered by galaxy interactions (Kennicutt 1991 and references therein). The luminosities involved in the UL galaxies, however, are large enough that starburst models are pushed to extreme levels to explain them: the models of Scoville and Soifer (1991) imply star formation rates of about 100 $M_\odot\,\mathrm{yr}^{-1}$ for a luminosity of $10^{12} L_\odot$ if the IMF is truncated below 1 $M_\odot$, and considerably more if the IMF extends below this mass. The obscured AGN idea follows from the fact that QSOs are the only other known objects that have been observed to be as luminous as the UL galaxies, and that the space densities of the two types of objects are not dissimilar. Moreover, AGNs arc also well known to be capable of strong far-infrared emission (Rieke and Lebosfsky 1979; Telesco 1988).

Two other energy sources have been advanced to explain far-infrared-bright galaxies. Heating by the kinetic energy of colliding galaxies was hypothesised by (Harwit *et al.* 1987); however this model predicts very short t imescales for the highest luminosity galaxies, which seem to be at variance with the observations. For example, the high luminosity-to-mass ratio for Arp 220 implies that the high luminosity can only be maintained for about 10^5 years (Sanders, Scoville and Soifer 1991). Secondly, Thronson *et* *al. (1* 990) suggested simply that heating by the old stellar population of very massive galaxies could account for the energy. Whilst an interesting possibility y for moderately luminous, undisturbed, infrared galaxies, this possibility dots not seem plausible for the ultraluminous galaxies for a number of reasons. First is the evidence cited above that wc are seeing an additional source of energy in the far-infrared emission rather than an increased obscuration of the old stellar population. Second, the fact that most (perhaps all) UL galaxies are in merging systems argues against a passive, galaxy-wide energy source. Thirdly, the extremely warm dust temperatures derived from the IRAS data for merging galaxies (Mozzarella, Bothun and Boroson 1991), and the compact source sizes, argue in favor of compact nuclear star formation and AGN dust heating sources instead of a cool interstellar radiation field due to old stellar populations

Given that the likely energy sources are starbursts and/or AGN, the UL galaxies become of key interest for the more general question of the connection between 'classical" AGN (a galaxy with a central black hole being fed by infalling material) and starbursts. Independently of the ultraluminous galaxies, classical AGN and starbursts have been linked to each other since they can occur in the same object, and both have been linked to some degree with galaxy-galaxy interactions and mergers (see Heckman 1991 a and Kennicutt 1991 and references therein). Thus the nature of the energy source(s) for the UL galaxies should be investigated with this more general context in mind. Some general possibilities for a connection between AGNs and starbursts include:

1) A causal and/or evolutionary connection. Perhaps tidal interaction triggers fueling of a prc-existing supermassive black hole, and the resulting AGN in turn triggers a starburst via shocks. Alternatively the starburst may occur first, creating fuel for the black hole and perhaps creating the broad-line regions from supernova winds (Perry and Dyson 1985) or the ablated atmospheres of giants (Norman and Scoville 1988), or even creating the black hole itself from the accumulated remnants of massive stars (Weedman 1983). In either case we might expect to scc some similarities between the host galaxies of A GN and starbursts and wc can search for an evolutionary sequence bet wccn these phenomena.

2) Common ancestry. Interactions and mergers trigger both AGN and starbursts but they do not necessarily trigger each other. In this case we can expect to scc these two kinds of phenomena in similar host galaxies on similar timescales, but wc do not necessarily expect to find any particular evolutionary sequence between starbursts and AGN.

3) There may be no connection, the two phenomena occurring essentially independently. In this case wc expect neither a similarity of host galaxies, nor simultaneous occurrence, nor an evolutionary sequence. This possibility can probably be ruled out since there is considerable evidence that both starbursts and AGN are linked to galaxy collisions. In addition, there are several examples of galaxies which host both an AGN and a starburst, for example N 1068 (Telesco *et al. 1984)* and NGC 2469 (Wilson *et al.* 1991).

4) The final, more controversial possibility is that AGN and starbursts are essentially the same phenomena; that is that "classical" AGN are in fact extreme starbursts and arc not powered by a central black hole at all (Terlevich 1992, and references therein). A class of massive, high metallicity, hot stars called "Warmers" is invoked to explain many AGN characteristics. Although this is an appealing scenario for some AGN, particularly Seyfert 2 galaxies, it cannot yet explain" all classical AGN phenomena, most notably

radio jets and superluminal motion, very rapid X ray variability (McHardy 1988), and the small scales of the emission components revealed by reverberation mapping studies of NGC 5548 (Peterson *et al.* 1991; Clavel *et al.* 1991). See the recent review by Heckman (1991b) for a discussion (but sec also Terlevich 1992). In addition, an apparent micro-lensing event in onc of the four gravitationally lensed images of the radio-quiet quasar Q2237+0305 implies a size for the emitting region for this object of $\sim 10^{16}$ cm (Corrigan *et al.* 1991).

3 SUMMARY OF KEY OBSERVATIONS

UL galaxies have now been observed with a tremendous range of instruments and techniques, but the nature of the energy source still remains unclear. Key initial observations used optical spectroscopy in order to search for broad lines characteristic of Seyfert 1s or QSOs, and for line ratio diagnostics of excitation. Most far-infrared-bright galaxies show narrow emission lines consistent with excitation by young stars, but close to the boundary of Seyfert-like line ratios in classical excitation line-ratio diagrams such as those of Baldwin, Phillips and Terlevich (1981). Very fcw UL galaxies can be classified as Seyfert l-like from their optical spectra, and those that are tend to be previously known Seyfert 1s. A larger percentage of objects can be classified as Seyfert 2 or Liner, and this percentage seems to increase with L_{IR} and with increasing 60/100 μm color temperature (Sanders *et al.* 1988a; Leech *et al.* 1989; Armus, Hcckman and Miley 1989). Such spectra do not necessarily prove the presence of a classical AGN however, as they can also be interpreted as due to shock emission (particular] y Liner spectra), or to Warmers.

The most convincing evidence for ongoing massive star formation would obviously come from the direct detection of spectral features due to such stars. Armus *et al.* (1988, 1989) have detected Wolf-Rayet emission lines in 2 or more ultraluminous galaxies. Rieke *et al.* (1985) and Wynn-Williams, Ridgway and Becklin (1993) have obtained near-infrared spectra, finding evidence for red supergiants from the depth of the CO bandhcad at 2.3 pm.

To determine whether the young stars implied by the optical and near-infrared spectroscopy can power the far-infrared sources, it is necessary to consider the energetics involved. Armus, Heckman and Miley (1990) have imaged several galaxies in Hα, finding large nebulae of varied structure, with a mean half light radius of 1.3 kpc. Estimates of the extinction imply much higher optical depths than typical of non-infrared-bright galaxies. After correcting for extinction using Hα/Brα line ratios where possible, Armus *et al.* (1990) find that the star formation rates implied by the I ICY luminosities arc on average about a factor of 3 too small to explain the far-infrared luminosity. This discrepancy could be explained in a number of ways, including underestimated extinction, an unusual IMF, a rapidly changing star formation history coupled with the fact that the far-infrared and Hα measure the star formation rate (SFR) over different periods of time, and an extra AGN heating source for the IR emission.

Imaging at far-infrared wavelengths would be an ideal way to distinguish between starburst and AGN power sources, since the for the latter case the infrared source would be expected to be very compact. Such observations are extremely difficult, duc to sensitivity limitations, and the need to usc airborne experiments beyond about 30μm. Recently, however, Telesco, Dressel and Wolstencroft (1993) have successfully mapped 21 gal axics between 10 and 30μm, while Wynn-Williams and Becklin (1993) have scanned 19 galaxies in the same wavelength range. Not all of the galaxies observed can be described as luminous or ultraluminous galaxies, however some do fall into this category. Both authors find that most of their sample are resolved at the few hundred parsec level by comparing their results to the flux densities measured by IRAS. It is striking, however, that non-the-less the infrared sources in many of these galaxies have small characteristic radii of 200 to 500 hundred parsecs, comparable to the sizes found at radio cm continuum wavelengths (Condon *et al.* 1990). Some galaxies in Wynn-Williams and Becklin's (1993) sample are unresolved by them, including Arp 220, with a diameter of < 700 pc.

Working on the hypothesis that the UL galaxies may be AGN that arc not easily observable as such in the optical because of high optical depth, a number of workers have searched for broad emission lines in the near-infrared. Evidence for dust enshrouded broad-line regions has been uncovered in a number of infrared luminous galaxies using near infrared spectroscopy, including Arp 220 (DePoy *et al. 1987),* IRAS 20460+-1925 and IRAS 23060+0505 (Hines 1991) and IRAS 14348-144 (Nakajima *et al.* 1991). Assuming the dusty material might be preferentially aligned to our line-of-sight, Young *et al. (1993)* have searched for broad lines in reflected polarized light, finding a strong broad Hα line in onc luminous galaxy.

Near-infrared imaging of Arp 220 and other UL galaxies has revealed strong color gradients, which are interpreted as evidence for increasing extinction and emission from warm dust as the nucleus is approached (Mozzarella *et al* 1991; Carico *et al. 1990).*

Molecular line observations of UL galaxies have proved very interesting, with the discovery of large H_2 masses (as implied by CO line observations) of $2 - 60 \times 10^9 M_\odot$, 1-30 times that of the Milky Way (Rickard and Harvey 1984; Sanders *et al. 1991).* Interferometer CO maps indicates that in many cases a large fraction of this gas is highly concentrated to the central region, with > 50% lying within the central kiloparsec (Scoville *et al. 1991*). The gas surface densities can reach values as high as 10^3 to $10^5 M_\odot/\mathrm{pc}^2$. Arp 220 has about 2 x $10^{10} M_\odot$ of molecular hydrogen within a radius of about 300 pc, which is comparable to the dynamical mass within this radius (Scoville *et al. 1991*). The column density inferred to the nucleus of Arp 220 results in an equivalent optical extinction of a staggering A_v=1 000 msg.!

l'here is a positive relationship between L_{IR} and L_{IR}/L_{CO} which has been interpreted as indicating that the star formation efficiency increases with L_{IR} (eg. Young *et al.* 1986) but which actually measures the rate that the molecular gas is used up by star formation (assuming star formation is the explanation of the far infrared-energy). This relationship could also be interpreted in several alternative ways, such as an additional heating source (an AGN as well as a starburst), or an increase in dust temperature such that a larger fraction of the total (40 – 500pm) far infrared luminosity is detected by the IRAS 60 and 100μm bands. There is some evidence that the more strongly interacting and merging systems have the highest ratio of L_{IR}/L_{CO} (Sanders *et al. 1991).*

An important recent observation is that of Solomon *et al., (1* 992), who have observed several UL galaxies in molecular lines of HCN, which traces the dense gas mass (10^{4-5} cm^{-3}) much better than the CO lines. They find that in contrast to the results for the lower density regions (< $10^3\,\mathrm{cm}^{-3}$) based on CO data, the dense gas mass correlates well, with slope unity, with the far-infrared luminosity. Since in our own Galaxy it is known that massive stars form in dense regions of giant molecular clouds, this result is consistent with a picture in which the central few hundred parsecs of UL galaxies resemble an enormous scaled-up giant molecular cloud.

Condon *et al. (1991)* have showed that many of the most luminous galaxies arc extremely compact in 8.4 GHz continuum VLA observations, of order 0".25, or about 100 pc at the typical distance of the sample. They nonetheless argue that the radio emission is consistent with a st arburst origin, based on arguments that the sources must be free-free absorbed at cm wavelengths, and optically thick in the far-infrared out to at least $25\mu m$; after correction for absorption the UL galaxies follow the well-known excellent correlation between far-infrared and radio emission found for star forming galaxies in general (van der Kruit 1971; Helou, Soifer and Rowan-Robinson 1985; Condon, Anderson and Helou 1991).

Norris *et al.* (1990; 1992) have used a medium baseline interferometer to search for compact radio cores in a variety of far-infrared bright and other active galaxies at 18 cm, including some ULS. 'l'he philosophy here is that detection by the interferometer implies a brightness temperat urc of greater than about 105 K, which is expected to be a good signature of a classical AGN, since starburst emission should not exceed about $10^{4.5}$K (Condon *et al.* 1991). Norris *et al.* found a higher detection rate for galaxies with other spectroscopic indicators of the prcscncc of an AGN, compared to galaxies with 1111-region or starburst excitations, and concluded that optical spectroscopic indicators for starbursts vs. AGN are quite reliable, even for apparently highly dusty objects. I will return to this approach in Section 5 below, where our recent VLBI observations arc discussed.

Ricke (1988) has argued that the non-detection of several UL galaxies in hard X-rays favors a starburst interpretation, since QSOS or Seyfert 1 galaxies of the these luminosities would have been easily detected in the hard X-ray regime hc considered. However, Ricke's results arc not inconsistent with an AGN origin for the far-infrared luminosity if the absorbing column between us and the AGN is high enough: greater than about 5 x1023 cm^{-2}. This is less than the column observed by Scoville and Sargent in Arp 220 (3.5 *x 1024* cm–2), but perhaps greater than that in most other UL galaxies (Ricke 1992).

Galactic supcrwinds have recently received much attention (scc Heckman, Lehnert and Armus 1993 for a comprehensive recent review). Believed to be powered by the combined energy of supernovae and the winds of massive stars from starbursts, these energetic winds of hot gas have been studied principally in X-rays and optical emission lines. Hcckman *et al. (1993)* describe work which shows that supcrwind indicators in 50 infrared-selected galaxies are correlated with J_{IR}, L_{IR}/L_B and far-infrared color temperature. Therefore, to the extent that it is indeed the case that these supcrwinds arc powered by starbursts rather than by AGN, these results support a st arburst interpret ation for the far-infrared emission.

Another intriguing phenomenon associated with luminous IR galaxies arc the OH megamasers, discovered by Baan *et al. (1982)*. Generated by amplification of a background radio continuum source by foreground OH molecules inverted by far-infrared radiation, megamasers imply the existence of high molecular optical depths along the line-of-sight to a nuclear radio source. L_{OH} has been found to increase roughly as L_{IR}^2, in agreement with the predictions of pumping models (Baan 1989), and over half of the UL galaxy sample of Sanders *et al. (1988a)* has a megamaser, suggesting that the covering factor of the molecular column over the nuclear radio source must be high in these objects as a class, Finally Desert and Dennefeld (1988) have observed features due to polycyclic aromatic hydrocarbons (l' Al Is) in several galaxies, and find evidence that PAHs are seen in starburst environments, but destroyed in the vicinity of strong AGN sources. PAH emission could therefore be a useful discriminant for many galaxies if careful high resolution mapping is available in the lines; however it seems likely that in the UL galaxies the optical depths could be so high that the PAH features could arise in regions well shielded from the strong hard UV / soft X-ray radiation field required to destroy the PAH molecules. For a recent discussion of the survivability of PAHs in AGNs, see Voit (1992).

4 SCENARIOS

Sanders *et al. (1988a)* have promoted a picture in which an interaction and merger has triggered an obscured QSO and this is the power source for the UL galaxies, with an evolutionary sequence from starburst through dusty obscured QSO to dust-free UV-bright QSO. This model is based on the similarity of the space density of classical QSOS and the UL galaxies at $L_{bol} > 10^{11.5} L_{\odot}$, and also on a sequence in continuum energy distribution shape from the IR-dominated UL galaxies, through a group of objects which are still quite far-infrared luminous but which have warmer far-infrared colors (Sanders *et al.* 1988b) to the UV-bright QSOs. This sequence is interpreted as an evolutionary sequence: first a starburst occurs, but this is insignificant in IR luminosity compared to the UL galaxies, or else it dies away very quickly. The starburst either creates, or simply precedes, a QSO phase. The QSO is initially very heavily obscured by the centrally concentrated dust and molecular gas which has fallen to the center duc to the loss of angular momentum caused by the shocks engendered during the interaction. During this phase the object appears as an UL galaxy. The new QSO and/or an associated starburst superwind, then steadily blows away the obscuring dust cloud, revealing first the 'closer, warmer dust, and finally a 'naked' UV-bright QSO.

Several modifications to this picture have been suggested. 'l'here is no compelling reason why the initial starburst could not be the dominant source of far-infrared energy in the early stages of this evolutionary sequence, and some lines of evidence suggest that a luminous AGN may not be created or revealed until a late stage, perhaps after the two nuclei of the interacting galaxies merge (Mozzarella *et al. 1991;* Baan 1988; Hutchings and Neff 1991; Majewski *et al.* 1993).

If there is a link, either evolutionary or otherwise, between UL galaxies and 'classical' AGNs, it is of interest to ask whether other classes of AGNs possess any of the striking properties of the far-infrared-selected UL galaxies: most importantly, luminous compact infrared sources with very large molecular gas masses. Mazzarella *et al. (1993)* have detected five of eight powerful radio galaxies observed in CO, finding H_2 gas masses of up to 2 x 10^{10} $M_{\odot}$. These objects arc indistinguishable from UI, galaxies in an $L_{IR}/M(H_2)$ vs. L_{IR} diagram, implying that there could be a similarity in physical conditions and/or evolutionary genesis of the two types of objects. Andreani, La Franca and Cristiani (1993) have found evidence for large masses of dust in 4 quasars ranging in redshift from 1.68 to 4.09.

An alternative scenario to the obscured QSO model is that of a compact starburst model with no need for a classical A GN. Promoted by several authors (eg. Rieke *et al.*

1985), the model was given a boost by the compact radio source observations of Condon *et al. (1991),* a key argument being the fact that the UL galaxies agree quite well with the seemingly universal radio-infrared correlation, as discussed above. Proponents of this scenario argue that high line excitation characteristic of Liners or Seyfert 2 galaxies could arise in shocks and Warmers. Broad emission lines could arise in superwinds.

Besides these two extreme scenarios, pictures in which both an AGN and a starburst contribute to the energy are not inconsistent with the currently available data. In fact, this is just what seems to be occurring in objects like NGC 1068, where the nucleus and a kpc-scale ring of star formation contribute about equally to the far-infrared emission (Telesco *et al.* 1984). Naturally, this interpretation complicates the issue of determining the ultimate power sources for the far-infrared emission in each individual UL galaxy. In reality it is quite possible that there is a spectrum of sources in which sometimes the AGN dominates, sometimes the starburst dominates, or there is a roughly equal split between the competing dust heating sources (see the conference proceedings edited by Filippenko 1992 for a summary of recent work on the starburst-AGN connection).

5 THE VLBI PROJECT

Lonsdale, Lonsdale and Smith (1992) and Lonsdale, Smith and Lonsdale (1993a) have extended the technique of Norris (1988) to higher brightness temperatures using global VLBI networks at 18 cm. Our motivation is to test the pure starburst models for UL galaxies by searching for a reliable AGN signature, Previous searches for AGN signatures in UL and similar galaxies have included optical line excitations, optical and near-infrared broad emission lines, and hard X-rays, as described above. Unfortunately the large amounts of intervening material strongly hamper all these techniques, even the detection of hard X-rays. Even when indicators of an AGN are found in the optical spectra they are ambiguous in interpretation because starburst phenomena can be invoked to explain them.

Radio continuum observations in the cm region are unaffected by dust obscuration and onl y mildly affected by free-free absorption. Moreover starbursts are not expected to radiate above brightness temperatures of about 105 K (Con don *et al. 1991)* so an experiment sensitive to higher brightness temperature sources is an excellent AGN detector.

Lonsdale, Smith and Lonsdale (1 993) observed 31 galaxies with L_{IR} > 1011 .251.0 (H=50 km/s/Mpc) and with compact VLA-scale (< 0.''25) 8.4 GHz sources, as measured by Condon *et al.* (1991). 18 of the 31 objects in the sample are detected with brightness temperatures $T_b >> 10^7 K$ and structure on scales of 5-150 mas, which corresponds to a few parsecs. Another 20% show structure on shorter baselines, corresponding to 105< T_b < 10^7K. All these objects are inconsistent with the compact starburst model of Con don *et al. (1991).* The median VLBI core power for detected sources is log P_{core} = 22 W Hz-l, and the median ratio of core-to-total 18 cm flux density is 12%. The limits for non-detected sources are similar, consistent with a picture in which most of these galaxies have compact cores at a level of a few percent of the total radio flux density. Two objects have $P_{core} \sim 0.5 P_{total}$: the well known Seyfert 1 galaxy Mrk 231, and a galaxy with pure HII-region-like emission lines, UGC 2369.

Unlike Norris *et al.* (1990; 1992), we found no correlation between detectability of high T_b emission and optical indicators of an AGN, including spectral line ratios. The main reason for this difference from Norris *et al.*'s results is that wc have focussed on the UL galaxies, while Norris looked at a much rnorc heterogeneous sample, including lower luminosity objects, which likely have smaller concentrations of dust obscuring their nuclei compared to the UL galaxies we observed. Also, our experiment is both more sensitive and designed to detect higher brightness temperature emission than that of Norris *et al.*.

Our observations strongly support the the presence of an AGN deeply buried inside many, and possibly all, luminous infrared galaxies; the only plausible alternative explanation for the high brightness temperature emission is complexes of hypothetical, extremely luminous radio supernovae within the central fcw hundred cubic parsecs (Lonsdale *et al. 1992;* Yin and Heeschen 1992). Structural and energetic considerations rule out single supernovae or complexes of supernovae of normal luminosity. On-going and future mapping and monitoring experiments can distinguish between the AGN and luminous RSNe alternatives.

Detection of deeply dust-obscured compact radio AGN cores inside luminous far-infrared galaxies dots not of course prove that the A GN is responsible for the far-infrared luminosity, just as the detection of spectral features from young massive stars dots not prove that a starburst powers the emission. To study this question further, an investigation of the energetics of the obscured AGN is very informative. To this end, Smith, Lonsdale and Lonsdale (1993) have compared their sample of UL galaxies to a sample of Radio Quiet Quasars (RQQs) from the Palomar-Green sample under the following assumptions: (1) The far-infrared luminosity of compact UL galaxies is reradiated UV/optical light whose origin is the same as the RQQs; (2) The 18 cm radio flux from the RQQs shares a common origin with the VLBI core emission detected in the UL galaxy survey. In other words, wc assume that RQQs arc naked UL galaxies.

Figure 2 shows the UV/optical luminosity of PG QSOS (Sanders *et al.* 1989) plotted against the 18 cm radio power extrapolated from the 6 cm flux densit y with spect ral index α = 0.7 (Kellerman *et al. 1989).* On the same figure we have plotted the far-infrared luminosity for our UL galaxy sample against the 18 cm VLBI *core* power. The distribution for the UL galaxy characteristics falls within the distribution for the RQQs, which show a clear UV/optical correlation. Thus it is clear that obscured RQQs like the I'G sample objects are quite capable of powering the far-infrared luminosity of the UL galaxies.

Several questions remain regarding this hypothesis that the UL galaxies are obscured RQQs. Most obviously is the question of what RQQs actually look like at VLBI resolution; our result suggests that they should have the bulk of their power in an unresolved compact core. Another issue concerns the the nature of the extended radio emission; why do UL galaxies follow the well-known radio-far-infrared correlation? Onc solution would be to assume that young stars arc not the fundamental link explaining the radio-far-infrared correlation. If a dense, dusty medium is stirred up with hard radiation and shocks, perhaps a well defined fraction of the input energy goes into relativistic electrons. In other words, surrounding a RQQ by a dense dusty medium may enhance the non-thermal radio power on a scale of a kiloparsec or less, as well as the far-infrared emission.

Fig. 2. *Comparison of the UV/optical power of the Radio Quiet Quasars (Sanders et al. 1989; filled squares) and the far-infrared luminosity of the VLBI sample of Lonsdale, Smith and Lonsdale 1993; + symbols), both* in *solar luminosity units, vs. the 18 cm radio continuum power (Watts). For the VLBI UL sample, only the core radio power is plotted. The RQQs have sufficient UV/optical energy to power the UL galaxies*

6 SOME IMPLICATIONS

Whether the UL galaxies are powered by starbursts or enshrouded QSOs, they have some important implications for our theories of galaxy formation and evolution. If they are powered by starbursts, then these objects could represent the formation of ellipticals by merger-induced dissipative collapse. There has long been dissent over the idea that elliptical galaxies could form this way, based principally on two objections: (1) that mergers are not likely to be able to produce central stellar surface densities high enough to reproduce the $r^{1/4}$ density profiles seen in elliptical; and (2) the specific globular cluster frequency of elliptical is too high compared to that of a pair of colliding spirals. Recent work indicates that both of these objections can be overcome (Schweizer 1992). Firstly, near-infrared imaging of merging systems do indeed reveal $r^{1/4}$ dependences (Wright *et al.* 1990; Stanford and Bushouse 1991). Secondly, the very high molecular gas densities being found in the UL galaxies do indeed possess the characteristics required to match elliptical galaxy core densities (Kormendy and Sanders 1992). Finally, there is evidence that globular clusters can form in the starburst conditions of the UL and other merging galaxies (Holtzman *et al.* 1992, Shaya *et al.* 1993).

The most extreme UL galaxy so far discovered is the z=2.23 object IRAS F1 0214+4724, which has the enormous far-infrared luminosity of about 5 x $10^{14} L_{\odot}$ (H=50 km/s/Mpc; q_0=0.5) (Rowan-Robinson *et al.* 1991). This object suffers from the usual UL galaxy problem - we can 't tell whether the energy source is a tremendous starburst or a deeply buried QSO (see Lonsdale 1992 and Lonsdale 1993 for more detailed discussions of the possible nature of this object). It is perhaps most natural to assume the object is a buried QSO since other QSOS of this order of magnitude of luminosity and redshift arc known, while certainly no star forming galaxy of this luminosity ever has been. On the other hand it has been shown that this object possesses an enormous mass of molecular gas; that it is in fact a galaxy made mostly of molecules instead of stars. These are just the sort of conditions which we might expect that long sought after mythical object, the protogalaxy, to possess,

Thus F10214+4724 could bc the first example of a protogalaxy. If so, it demonstrates that PGs are very dusty, and that there must have been very rapid chemical enrichment. An alternative to this conclusion is to assume that F10214+4724 had a previous episode of star formation to generate the metals and dust; this episode would have had to occur at least 10^9 years ago if wc assume that, as in our Galaxy, it is evolved intermediate mass stars that arc responsible for the dust formation. However this scenario of two star formation episodes seems unlikely given the facts that (1) most of the mass of the object is still in the form of gas, not stars, and (2) the current star formation rate is high enough to form the entire gas mass into stars in just a few x 10^7 years. Elbaz *et al.* (1 992) have considered an enrichment model for F1 0214+4724 and find that both the metals and dust can bc generated in less than 10s years if the dust is formed in supernova remnants. At the apparent rate of dust formation of SN 1987A (Dwek *et al.* 1992) the supernova rate of F1 0214+4724 is indeed high enough to generate the required dust mass,

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References

Andreani, P., La Franca, F., and Cristiani, S.:)993, *Mon. Not. R. Astr. Sot.*, in press

Armus, L., Heckman, T. M., and Miley, G. K.: 1988, *Astrophys. J.* 326, L45

Armus, I.., Hcckman, T. M., and Miley, G. K.: 1989, *Astrophys. J.* 347, 727

Armus, L., Heckman, T. M., and Miley, G. K.: 1990, *Astrophys. J.* 364,471

Baan, W. A.: 1988, *Astrophys. J.* 330, 743

Baan, W. A.: 1989, *Astrophys. J.* 338, 804

Baan, W. A., Wood, P., and Haschick, A.D.: 1982, *Astrophys. J.* 260, 1.49

Baldwin, J. A., Phillips, M.M, and Terlevich, R.: 1981, *Publ. Astr. Sot. Pac.* 93, 5

Bothun, G. D., Lonsdale, C. J., and Rice, W. L.: 1989, *Astrophys. J.* 341, 129

Carico, D. P., Graham, J. R., Matthews, K., Wilson, C. D., Soifer, B. T., Neugebauer, G., and Sanders, D.B.: 1990, *Astrophys. J.* 349, 1,39

Clavel, J. *et al.: 1991, Astrophys. J.* 366, 64

Condon, J. J., Anderson, M.I,., and Helou, G.H.: 1991, *Astrophys. J. 376, 95*

Condon, J. J., Helou, G., Sanders, D.B., and Soifer, B. T.: 1990, *Astrophys. J.-Suppl. Ser.* 73, 359

Condon, J. J., Huang, Z.-P., Yin, Q. F., and Thuan, T. X.: 1992, *Astrophys. J. 378,* 65

Corrigan, R.T. *et al.*: *1991, Astron. J.* 102, 34

]) ePoy,]).],., Becklin, E.E., and Geballe, T. R.: 1987, *Astrophys. J.* 316, L63

Desert, F. X., and Dennefeld, M.: 1988, *Astr. Astrophys.* 206, 227

Dwek, E. Moseley, S.11., Glaccum, W., Graham, J. R., Loewenstein, R. F., Silverberg, R. F., and Smith, R.K.: 1992, *Astrophys. J.* 389, L21

Efstathiou, G., Ellis, R. S., and Peterson, B. A.: 1988, *Mon. Not. R. Astr. Soc.* 232,431

Filippenko, A.: 1992, ***Relationships between Active Galactic Nuclei and Starburst Galaxies***, Astron. Sot, Pacific. Conf. Series, 31

Graham, J. R., Carico, D. P., Matthews, K., Neugebauer, G., Soifer, B.T., and Wilson, C. D.: 1990, ***Astrophys. J. 354,*** L5

Harwit, M. O., Houck, J. R., Soifer, B. T., and Palumbo, G. G. C.: 1987, ***Astrophys. J. 315, "28***

Heckman, T. M.: 1991a, in ***Paired and Interacting Galaxies,*** ed. J. Sulentic, W. Keel, and C. M. Telesco, NASA Publication 3098, p. 359

Heckman, T. M.: 1991 b, in ***Massive Stars in Starburst Galaxies,*** cd. C. Leitherer, N. Walborn, T. Heckman, and C. Norman, Cambridge: Cambridge University Press, p. 289

Heckman, 'l'. M., Lehnert, M. D., and Armus, L.: 1993, in ***Evolution oj Galaxies and Their Environments,*** in press

Helou. G., Soifer, B. T., and Rowan-Robinson, M.: 1985, *Astrophys. J.* 298, L7

Hines, D. C,: 1991, ***Astrophys. J. 374, 1.9***

Holtzman, J.A. *et al.*: 1992, *Astron. J.* 103, 691

Hutchings, J.El., and Neff, S. G.: 1991, ***Astron. J. 103, 1746***

Kellerman, K, I., Sramek, R., Schmidt, M., Shaffer, D.B., and Green, R.: 1989, ***Astron. J. 98, 1195***

Kennicutt, R. J.: 1991, in ***Paired and Interacting Galaxies***, cd. J. Sulentic, W. Keel, and C. M. Telesco, NASA Publication 3098, p. 269

Kormendy, J., and Sanders, D.B.: 1992, ***Astrophys. J. 390,*** L53

Leech, K. J., Penston, M. V., Terlevich, R.., Lawrence, A., Rowan-Robinson, M., and Crawford, J.: 1989, ***Mon. Not. R. Astr. Sot. 240, 349***

Lonsdale, C. J.: 1992, in ***First Light in the Universe,*** cd. B. Rocca-Volmerange

Lonsdale, C. J.: 1993, to appear in ***Extragalactic Background Radiation,*** ed. I). Calzetti, M. Fall, M. Livio, and P. Madau, Cambridge: Cambridge University Press

Lonsdale, C. J., Lonsdale, C. J., and Smith, H.E.: 1992, *Astrophys. J.* **391**, ***629***

Lonsdale, C. J., Smith, H.E., and Lonsdale, C. J.: 1993, ***Astrophys. J. 405,*** L9

Majewski, S. R., Hereld, M., Koo, D. C., Illingworth, G. D., and Heckman, T. M.: 1993, ***Astrophys. J. 402, 125***

Mazzarella, J. M., Bothun, G. D., and Boroson, T. A.: 1991, ***Astron. 3.101,*** 2034

Mozzarella, J. M., Soifer, B. T., Graham, J. R., Hafer, C. I., Neugebauer, G., and Matthews, K.: 1991, *Astron. J.* 103, 413

Mazzarella, J .M., Graham, J. R., Sanders, D.B., and Djorgovski, S.: 1993, ***Astrophys. J. .409, 170***

McHardy, I.: 1988, ***Mere. Sot. Astron. Ital. 59, 239***

Nakajima, T., Kawara, K., Nishida, M., and Gregory, D.: 1991, ***Astrophys. J. 373, 452***

Norman, C. A., and Scoville, N. Z.: 1988, ***Astrophys. J. 332, 124***

Norris, R. P., Allen, D. A., Sramek, R. A., Kesteven, M. J., and Troup, E.R.: 1990, *Astrophys. J. 359,* 291

Norris, R. ., Roy, A. L., Allen, 1). A., Kesteven, M. J., Troup, E.R., and Reynolds, J. E.: 1992, in ***Relationships between Active Galactic Nuclei and Starburst Galaxies***, Astron. Sot. Pacific. Conf. Series, 31, ed. A. V. Filippenko, p. 71

Perry, J. J., and Dyson, J. E.: 1985, ***Mon. Not. R. Astr. Sot. 213, 665***

Peterson, B.M. *et al*: 1991, ***Astrophys. J. 368, 119***

Rickard, L. J., and Harvey, P. M.: 1984, ***Astron. J. 89, 1520***

Rieke, G.H.: 1988, ***Astrophys. J. 331, 1.5***

Rieke, G. H.: 1992, in ***Relationships between Active Galactic Nuclei and Starburst Galaxies,*** Astron. Sot. Pacific. Conf. Series, 31, ed. A. V. Filippenko, p. 61

Rieke, G.H., amd Low, F. J.: 1972, ***Astrophys. J. 176, 1,95***

Rieke, G. H., and Lebofsky, M. J,: 1979, ***Ann. Rev. Astron. Astrophys., 17,477***

Rieke, G. H., and Lebofsky, M. J,: 1986, ***Astrophys. J. 304, 326***

Rieke, G.]]., Cutri, R. M., Black, J.H., Kailey, W. F., McAlary, C. W., Lebofsky, M. J., and Elston, M. J.: 1985, ***Astrophys. J. 290,*** 116

Rowan-Robinson, M.: 1991, in ***Dynamics of Galaxies and Their Molecular Cloud Distributions,*** ed. F. Combes, and. F. Casoli, Kluwer: Dordrecht, p. 21 1

Rowan-Robinson, M., ***et al.:*** 1991, ***Nature 351, 719***

Sanders, D. B.: 1992, in ***Relationships between Active Galactic*** Nuclei ***and Starburst Galaxies,*** Astron. Sot. Pacific. Conf. Series, 31, ed. A. V. Filippenko, p. 303

Sanders, D. B., Scoville, N. Z., and Soifer, 13."1'.:1991, ***Astrophys. J. 370, 158***

Sanders, D.B., Soifer, B. T., Elias, J.H., Madore, B. F., Matthews, K., Neugebauer, G., and Scoville, N. Z.: 1988, ***Astrophys. J. 325, 74***

Sanders, D.B., Soifer, B. T., Elias, J. H., Neugebauer, G., and Matthews, K.: 1988b, ***Astrophys. J. 328,*** L35

Sanders, D.B., Phinney, E.S., Neugebauer, G., Soifer, B. T., and Matthews, K. Y.: 1989, ***Astrophys. J. 347, 29***

Saunders, W., Rowan-Robinson, M., Lawrence, A., Efstathiou, G., Kaiser, N., Ellis, R. S., and Frenck, C.S: 1990, ***Mon. Not. R. Astr. Sot, 242, 318***

Schweizer, F.: 1992, in Physics ***of Nearby Galaxies: Nature or Nurture?***, ed. T. X. Thuan, C. Balkowski, and J. Tran Thanh Van, Frontieres, Gif Sur Yvette

Scoville, N. Z., and Soifer, B.T.: 1991, in ***Massive Stars*** in ***Starburst Galaxies,*** cd. C. Leitherer, N. Walborn, T. Heckman, and C. Norman, Cambridge: Cambridge University Press, p. 233

Scoville, N. Z., Sargent, A. I., Sanders, D. B., and Soifer, B. Y.: 1991, ***Astrophys. J. 366,*** L5

Shaya, E., ***et al,:*** 1993, in press

Smith, H. E., Lonsdale, C. J., and Lonsdale, C. J.: 1993, in preparation

Soifer, I].'I'., Sanders, 1). B., Madore, B.F., Neugebauer, G., Danielson, G. E., Elias, J. H., Lonsdale, C. J., and Rice, W.],.: 1987, ***Astrophys. J. 320, 238***

Solomon, P. M., Dowries, D., and Radford, S. J. E.: 1992, ***Astrophys. J. 387,*** L55

Stanford, S. A., and Bushouse, H. A.: 1991, ***Astrophys. J. 371, 92***

Telesco, C. M.: 1988, ***Ann. Rev. Astron. Astrophys., 26, 343***

Telesco, C. M., and Harper, D. A.: 1980, ***Astrophys. J. 235, 392***

Telesco, C. M., Dressel, L. L., and Wolstencroft, R.]).: 1993, preprint

Telesco, C. M., Becklin, E.E., Wynn-Williams, C. G., and Harper, D. A.: 1984, *Astrophys. J. 282, 427*

Terlevich, R.: 1992, in *Relationships between Active Galactic Nuclei and Starburst Galaxies,* Astron. Sot. Pacific. Conf. Series, 31, ed. A. V. Filippenko, p. 133

Thronson, H. A., and Harper, D. A.: 1979, *Astrophys. J. 230, 133*

Thronson, H. A., Majewski, S., Decartes, L., and Hereld, M.: 1990, *Astrophys. J. 364, 456*

van der Kruit, P. C.: 1971, *Astr. Astrophys. 15,* 110

Voit, G. M.: 1992, *Astrophys. J. 399, 495*

Weedman, D. W.: 1983, *Astrophys. J. 266, 479*

Wilson, A. S.: 1991, *Astrophys. J. 381, 79*

Wright, G.S., James, P. S., Joseph, R.D., and McLean, I: 1990, *Nature 344, 417*

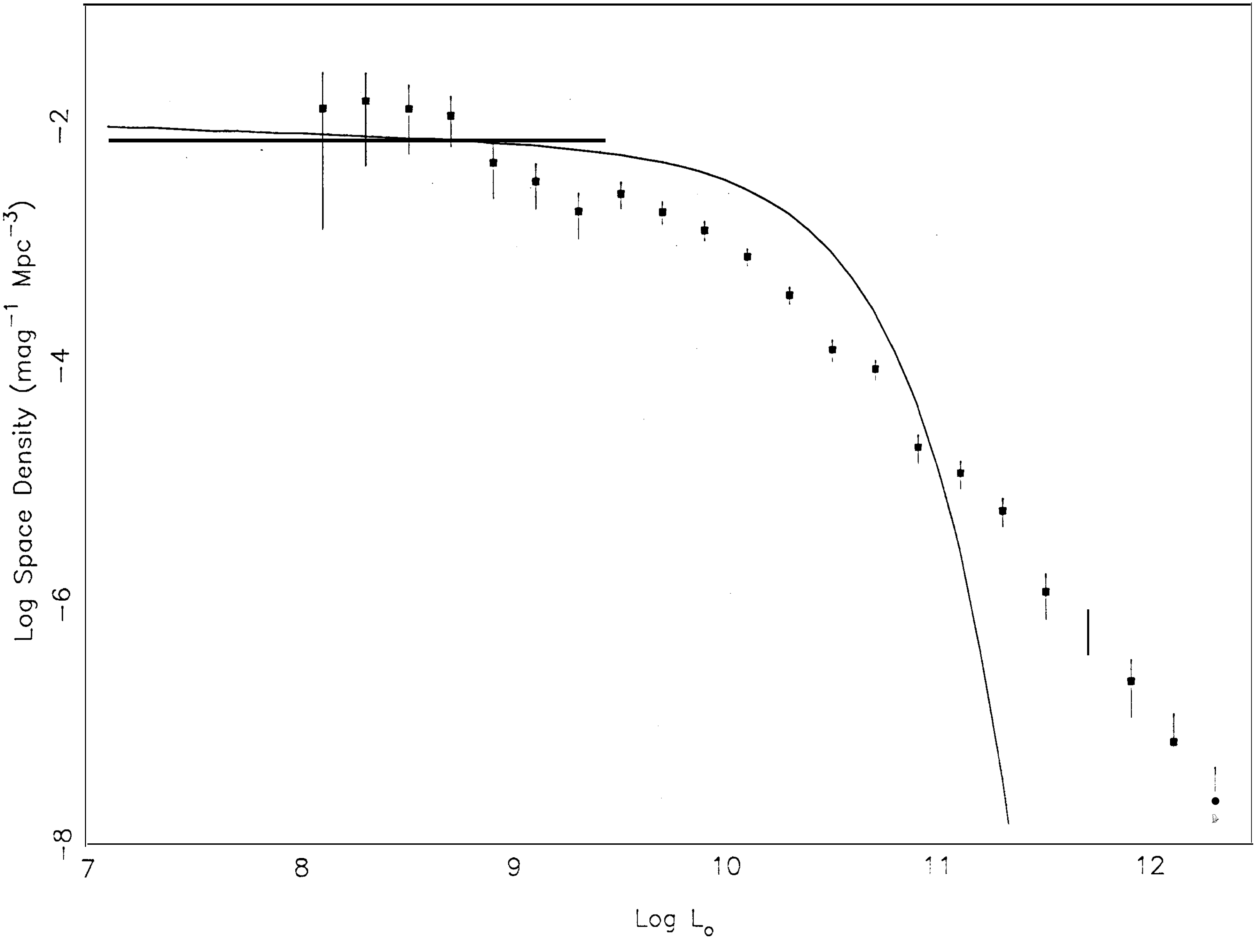
Wynn-Williams, C. G., and Becklin, E.E.: 1993, preprint

Wynn-Williams, C. G., Ridgway, S. E., and Becklin, E.E.: 1993, B. .A.A S, *25, 868*

Yin, Q. F., and Heeschen, D. S.: 1991, *Nature 354,* 130

Young, J. S., *et aL: 1986, Astrophys. J. 311,* L17

Young, S., Hough, J. H., Bailey, J. A., Axon, D. J., Ward, M. J.: 1993, *Mon. Not. R. Astr. Sot. 260,* L1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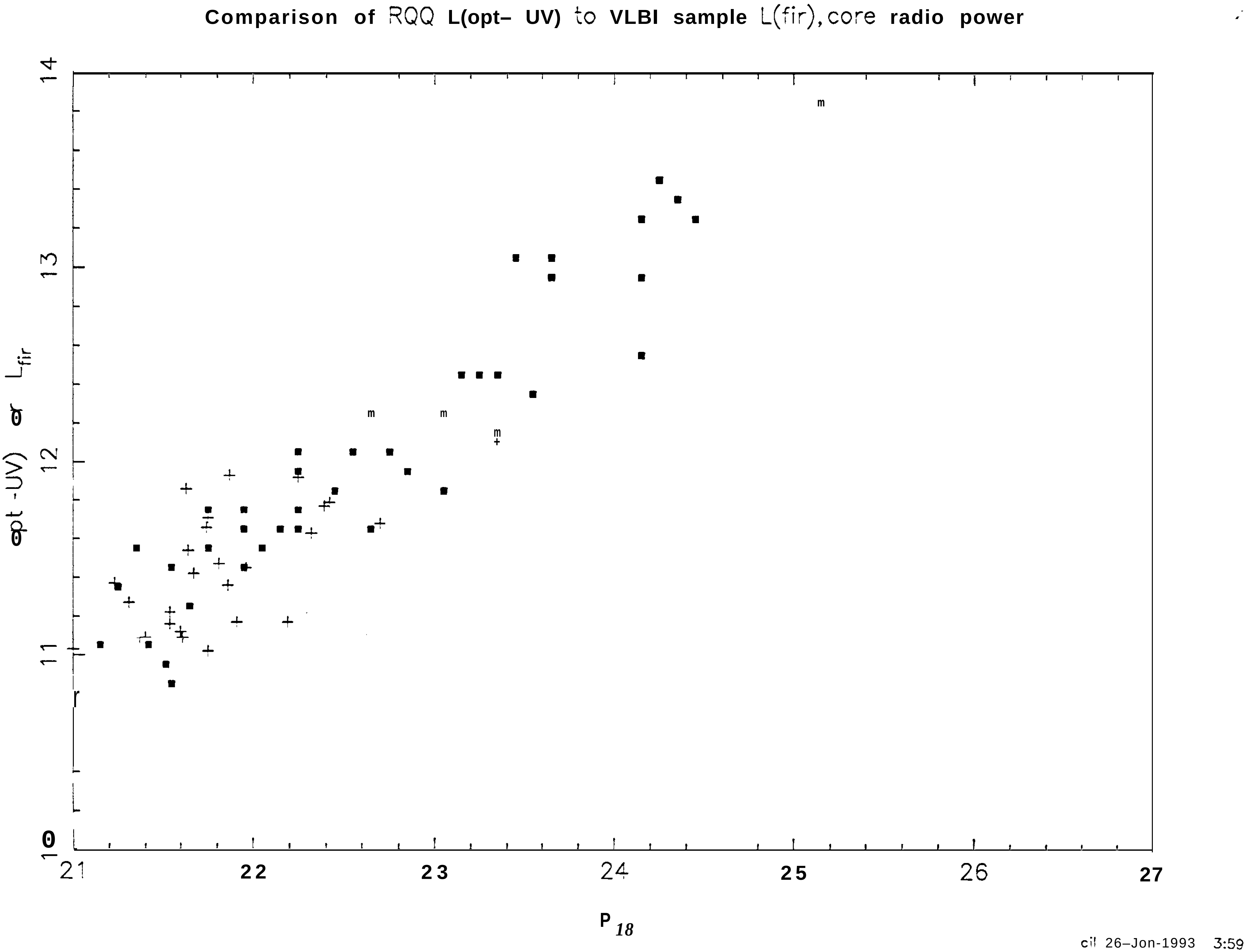

Comparison of RQQ L(opt– UV) to VLBI sample L(fir), core radio power
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